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Test Method

The viscoelastic response of soft material: A theoretical and experimental study based on barreling deformation

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ABSTRACT

The viscoelastic properties of polydimethylsiloxane (PDMS) measured are demonstrated by the uniaxial indentation test. Based on the barreling deformation, the viscoelastic models are established and the factors influencing the viscoelastic properties are discussed. These results indicate that the deformation response is greatly associated with load conditions and the PDMS materials exhibited more elastic properties at large load conditions as compared to small load conditions. It was reasonable to use the stress at the middle-section zone to investigate the viscoelastic behavior of the soft materials. The number and type of these elements in viscoelastic models affected the soft materials characteristics. These results would be helpful to further understand the viscoelastic properties and characterization of soft tissues.

1. Introduction

A few soft tissues, such as oral tongue, human joints and skins, exist in nature [1–3]. It is of great importance to explore and imitate the properties of these soft biologic materials. For instance, in order to imitate the oral processing of certain food items, the bionic tongue or palate soft materials should be prepared and utilized to estimate the relative performance with respect to food items.

The viscoelastic properties differentiate soft materials from hard materials, which are being theoretically and experimentally explored by the research community. The indentation method is mostly adopted to investigate the viscoelastic properties of soft materials due to the ease of specimen preparation and experimental procedure [4]. The different shape intenders, such as pyramidal intender [4,5], spherical tip [6–11] and flat-ended indenter [12–14], are utilized to investigate the viscoelastic properties. The spherical indenter produces local deformation and the pyramidal indenter breaks the contact surface. Therefore, the flat-ended indenter, with diameter more than the specimen, is used to reduce the material damage and results in uniform stress distribution. In addition, the nano-indenter tests are used to study their viscoelastic properties in a few experiments [5–7,13–18]. At the same time, the theoretical simulation methods, such as finite element method [18–20] and dynamic mechanical analysis [21], are employed to estimate the viscoelastic properties of soft materials.

The rheological model is one of the most common methods to characterize the viscoelastic properties of soft materials, which determines the relationship between stress and strain under the action of external forces [22–28]. The standard models, such as Maxwell model, Kelvin model and Burgers model, have been designed based on the elastic and viscous elements of different numbers, which can be obtained by the experimental results [29–32]. The accurate measurement of stress-strain relationship is an important challenge, particularly for different shape indenters. Moreover, the uniaxial indentation is a common technique to investigate the viscoelastic properties of soft materials, but it results in material barreling due to the two-end narrow and middle-section wide shape. If the friction between the material surface and the indenter is ignored, the expansion phenomenon becomes more prominent. At this point, the stress in various zones is significantly different. For instance, the stress in the two-end surface zone would be greater than that of other zones. These results can be analyzed in terms of mechanical properties of soft materials. To date, the rheological model, based on the barreling deformation, has rarely been involved in the study of soft materials.

The soft material, polydimethylsiloxane (PDMS), is being widely used due to its outstanding properties and low price [33]. By varying the amount of cross-linker and process parameters, a number of different polymers can be synthesized and utilized in various fields, such as coating, micromachining, biomedical treatment and bionics substitutes [34–38]. It has been verified that the characteristics of smooth PDMS and pig's tongue, such as roughness, wetting and deformability,

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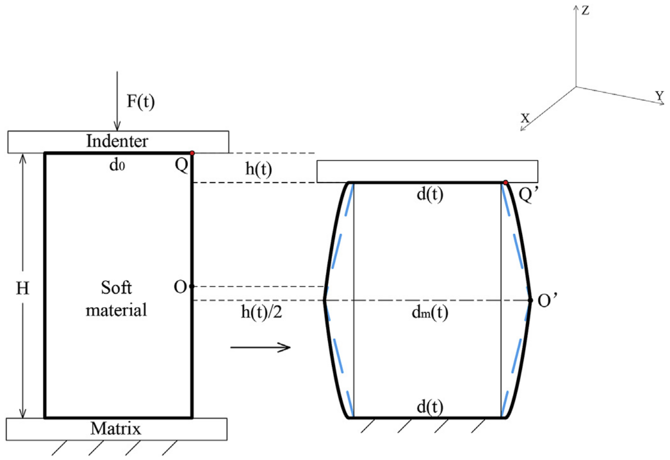

Fig. 1. Deformation schematic of the typical soft material under the external load.

are comparable, which indicates that the PDMS can be modified to match the characteristics of human tongue [36]. In recent years, the viscoelastic properties of various PDMS materials have been widely explored [39,40].

In the study, the PDMS is characterized using the uniaxial load test, without constraining its two-end surface, by means of the flat indenter. The stress and strain relationship is investigated based on barreling deformation under different loads and rheological viscoelastic models are established. The factors influencing the viscoelastic properties are discussed. These results would be helpful to further understand the viscoelastic performance and characterization methods of soft tissues.

2. Method and materials

2.1. Barreling deformation of the typical soft material

The cylindrical soft material specimens were compressed by the plate indenter, as shown in Fig. 1. The diameter of the indenter plane was larger than the soft material specimen. It has been emphasized that the top and bottom surfaces of the soft material are not restrained by the indenter and the matrix, respectively. Under the action of uniaxial force, the specimen resulted in obvious deformation and the position in the coordinate system changed. For instance, the position of the rightmost point, on the top surface, was changed from Q to Q'. At the same time, the cylindrical shape of the soft material was converted into the complicated form. This kind of deformation can be referred as the barreling deformation.

From the macroscopic mechanics analysis, the stress $\sigma(t)$ and strain $\varepsilon(t)$ of the soft material, under the single directional force, are as following

$$\sigma_z(t) = \frac{4F(t)}{\pi d^2(t)} \tag{1}$$

$$\varepsilon_z(t) = \frac{h(t)}{H} \tag{2}$$

where $F(t)$ represents the external force, H corresponds to the original height, $h(t)$ refers to the displacement of the top surface to the original top surface, d_0 represents the original diameter of the top surface, $d(t)$ corresponds to the deformation diameter of the top surface and $d_m(t)$ refers to the deformation diameter of the middle section. From the viscoelastic law [41], assuming that a rheological material is isotropic, the uniaxial force F results in given stress-strain relationship,

$$\sigma_z(t) = \frac{E_A}{(1+\nu)}\varepsilon_z(t) \tag{3}$$

where E_A and ν correspond to the composite elastic modulus and Poisson's ratio of the isotropic material, respectively. In addition, a shape factor has been used widely in the design of elastomeric components to exploit the ability to have different stiffness in different modes of deflection deformation, and was the ratio of the loaded area to the force-free area [22]. In the current study, the area of the indenter was higher a bit than that of PDMS sample, and the loaded area was $\pi d(t)^2/4$. The force-free area was the lateral area of the barreling cylinder and was approximately $0.5\pi*(d(t)+d_m(t))*((d_m(t)\text{-}d(t))^2+h(t)^2)^{1/2}$. However, due to the incompressible nature of the soft material, the total volume before and after deformation remained same. The total volume can be given as,

$$V = \pi d_0^2 H/4 = \pi[H - h(t)][d^2(t) + d_m^2(t) + d(t)d_m(t)]/12 \tag{4}$$

As the $h(t)$is significantly small, the local variation in d_0 and $d(t)$ can be neglected, which implies that $d(t) \approx d_0$, and the diameter $d_m(t)$ and a shape factor can be both easily obtained. Therefore, the time-dependent stress and strain relationship can be established at a given time. What's more, due to the fact that shear/deflection deformation was not mentioned, a shape factor correction was not applied in this study.

2.2. Viscoelastic model of the 5-element

The 5-element mixed model was proposed to describe the viscoelastic properties of typical soft materials, as shown in Fig. 2. The E and η correspond to the elastic modulus and viscous coefficient, respectively. The differential equation for the soft material is given as following,

$$\frac{E_1+E_2+E_3}{E_1}\frac{d^2\sigma(t)}{dt^2} + \left[\frac{E_2+E_3}{\eta_1} + \frac{E_2(E_1+E_3)}{E_1\eta_2}\right]\frac{d\sigma(t)}{dt} + \frac{E_2E_3}{\eta_1\eta_2}\sigma(t) = (E_1+E_3)\frac{d^2\varepsilon(t)}{dt^2} + \frac{E_2E_3}{\eta_2}\frac{d\varepsilon(t)}{dt} \tag{5}$$

Two load modes were carried out in the current study, as shown in Fig. 3. The first stage was the linear load mode, as the external load increased linearly from 0 to F_O, within the time (τ_O). Afterward, the external load remained stable. In the first stage, the stress-strain equation for the 5-element model can be obtained by using the Laplace transformation,

$$\varepsilon(t) = \frac{\sigma_0}{\tau_0}\left[\frac{1}{2\eta_1}t^2 + \frac{E_1+E_3}{E_1E_3}t - \frac{\eta_2}{E_3^2} + \frac{\eta_2(E_2+E_3)}{E_3^2}e^{-\frac{E_2E_3}{\eta_2(E_2+E_3)}t}\right] \tag{6}$$

Where σ_O refers to the stress at the load F_O. For the second stage, the stress-strain equation can be given as follow:

$$\varepsilon(t) = \sigma_0\left[\frac{1}{\eta_1}(t-\tau_0) + \frac{E_1+E_3}{E_1E_3} - \frac{E_2}{E_3}e^{-\frac{E_2E_3(t-\tau_0)}{\eta_2(E_2+E_3)}}\right] \tag{7}$$

In above equations, the two parameters τ_O and σ_O can be easily defined, whereas the strain $\varepsilon(t)$ can be measured by the indentation test. Therefore, the remaining 5-element parameters can be deduced according to the indentation test.

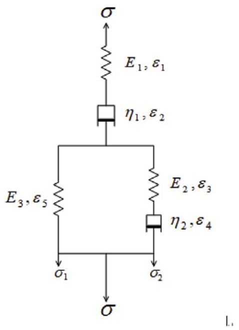

Fig. 2. Schematic illustration of the 5-element viscoelastic model.